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RESULTS OF OBSERVATIONS OF THE POLARIZATION EFFECT FOR SPORADIC METEORS

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RESULTS OF OBSERVATIONS OF THE POLARIZATION EFFECT FOR SPORADIC METEORS

E. K. Nemirova[1]

ABSTRACT: Methods and results of observations of the polarization effect accompanying the diffuse reflection of radio waves by meteor trails with a sporadic background at a wavelength λ = 10 m are presented.

Introduction

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Theoretical and experimental studies of the scattering of radio waves by meteors have shown that the polarization effect is an important factor in radio location of meteor tracks [1 et al.].

The dependence of the parameters of the reflected signal on the polarization of the incident wave relative to the axis of the track may constitute a difficulty in the experimental determination of certain characteristics of meteors [2, 3]. In observing continuous meteors with a known radiant it is possible to eliminate practically all of the disturbing effect of the polarization effect by orienting the antenna in such a way that the vector $\vec{E}$ of the incident wave is parallel to the trajectories of the meteor bodies. However, in the case of a sporadic background this possibility does not exist, since the meteor tracks are oriented in space in random fashion. Therefore the experimental investigation of the polarization effect for a sporadic background is very important.

The first attempt at an experimental investigation of resonance in meteor tracks was made in [4]. The experiments were conducted at the $\lambda \approx 9$ m wavelength during sporadic background. However, the experimenters did not succeed in detecting the polarization effect due to the incompleteness of their method of observation.

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[1]Ryazan Radio Technical Intitute.

*Numbers in the margin indicate pagination in the foreign text.

Successful observations of resonance for continuous meteors were made in [5] at $\lambda = 4.2$ m and in [6] at $\lambda = 5.4$ m. The results of the observations are basically in accordance with the theory.

The resonance effect for sporadic meteors was observed in [7] at $\lambda =$ /30
$= 13.1$ m. The method which was used made it possible to obtain an estimate of the upper limit of the polarization ratio, which was less than 4 for 80% of the reflections that showed the resonance effect.

The behavior of the phase of the reflected signal in resonance was studied in [8], and also in [3] using a more complete method. Several data on the experimental study of the polarization effect were obtained by M. F. Lagutin [9].

The present paper presents the results of observations of the polarization effect at $\lambda = 10$ m for meteors with a sporadic background. The results were obtained by an analysis of the amplitude-time characteristics for two types of polarization.

1. Principal Conclusions of the Theory

A study of the scattering of radio waves by a cylindrical track, expanding due to diffusion, will show that in the case of non-compressed tracks (linear electron density $\alpha < 2.4 \cdot 10^{12}$ electrons/cm) the reflectivities depend on the orientation of the $\vec{E}$ vector of the wave relative to the axis of the track [1]. With perpendicular polarization, resonance of the plasma develops when a dielectric permeability along the axis of the track $\varepsilon = -1.4$ (for a Gaussian distribution of the volume electron density along the cross-section of the track). The resonance effect leads to an increase of the modulus and a change in the phase of the scattering coefficient relative to the case of parallel polarization. The ratio of the modulus ρ (polarization ratio) and the phase shift φ of the scattering coefficients are shown in Figure 1. According to the theory, the maximum polarization ratio is 2.

The cylindrical model of the track is approximate. The model in the form of a paraboloid of rotation [6, 10] is more precise. The resonance effects can then occur only in a small part of the track which is near its origin. The length of the resonating section

$$l_{res} \cong 0.65 \cdot 10^{-13} \frac{a\lambda^2}{\pi^2 D} v,$$

where D is the diffusion coefficient and v is the velocity of the meteor.

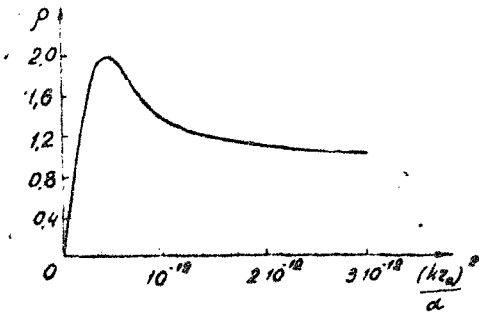

Figure 1. Polarization Ratio as a Function of $(kr_0)^2/\alpha$, where $k = 2\pi/\lambda$, r_0 is the track radius [1].

For a paraboloidal track, the degree of influence of the resonance effect on the parameters of the reflected signal depends on the ratio $l_{res}/\sqrt{R\lambda}$ (R equals range). Calculation of the paraboloidality of the track [10] made it possible to detect certain effects which were missing when a cylindrical model was used for the calculations. These effects are included in the hysteresis of the diffraction diagram, the change in periods and the height of the pulsations. The polarization ratio and the phase shift were found to be dependent upon $l_{res}/\sqrt{R\lambda}$

The calculations for both the cylindrical and paraboloidal tracks show /31 that the polarization effect is significant when the initial radius of the track $r_i \ll \lambda$. Hence, the resonance effects will be observed basically in the lower part of the meteor zone and will be more markedly evident when working at longer waves.

The theoretical consideration of resonance scattering was conducted in all cases on the basis of the assumption that the observation involved a single meteor which had certain physical parameters. However, in evaluating the degree of influence of the polarization effect on the observation results from a large number of meteors, having different masses, velocities, etc., especially with their random orientation in space, it is necessary to know that the statistical characteristics of this effect. The observations whose results are described below were aimed at these goals.

2. Method and Apparatus

The observations of the polarization effect were conducted on meteors with a sporadic background in March 1962 using the instrument at the Tomsk Polytechnic Institute. The parameters of the apparatus are as follows: wavelength λ = 10 m; pulse power in one antenna (taking into account the damping in the feeder) P_u = 17 kW; sensitivity of the receiver $\varepsilon_{min} \simeq 3.5 \cdot 10^{-13}$ W; the pulse duration τ_u = 5 μsec; the repetition frequency F_u = 600 pulses/sec; with every other impulse being double.

The station transmitter operated simultaneously only two antennas of the "wave channel" type, with polarization of one antenna in the horizontal plane and the other in the vertical plane. The coefficient of directional operation of each antenna G = 10. Both antennas were connected to a common receiver alternately (at intervals of 1 scanning). The station indicator made it possible to determine the range and the amplitude-time pattern for scanning times with a duration of 0.1 sec and 1 sec.

The minimum electron density which was measured with the aid of this apparatus may be calculated approximately with the following formula [11]:

$$\alpha^2_{min} = \frac{n^2 \varepsilon_{min} R^3}{3{,}3 \cdot 10^{-26} P_u G^2 \lambda^3},$$

where n is the signal-to-noise ratio as a function of voltage. For n = 5 and a range R = 150 km, $\alpha_{min} \approx 2.5 \cdot 10^{11}$ electrons/cm.

In performing the experiment, both antennas were set at an elevation β = = 45° and aimed toward the north. Observations were conducted during the night and morning hours during the period from 16 March to 1 April 1962.

Photographic film was used to record the time of appearance of a meteor, the range and the amplitude-time curve. An example of a print from one frame of the film is shown in Figure 2.

In analyzing the results of the observations of the polarization properties of sporadic meteors according to the method described, it is necessary to take into account a number of side effects. First of all, in order to

obtain the polarization effect "in pure form" the vectors $\vec{E}_1$ and $\vec{E}_2$ of the field swept by the antennas must be orthogonal at the point of reflection from the meteor track. Secondly, the track must be arranged parallel to one of /32 these vectors. The condition of orthogonality is fulfilled exactly only along the axis of the antenna diagram and in the planes which pass through the vibrators and the axis of the antenna. The reflecting points for sporadic meteors may have different angular displacements relative to the antenna axis within the limits of the directionality diagram. This necessarily leads to a certain decrease in the degree of appearance of the polarization effect. We can also assume that meteors that show a polarization effect must be concentrated near the maximum of the major lobe.

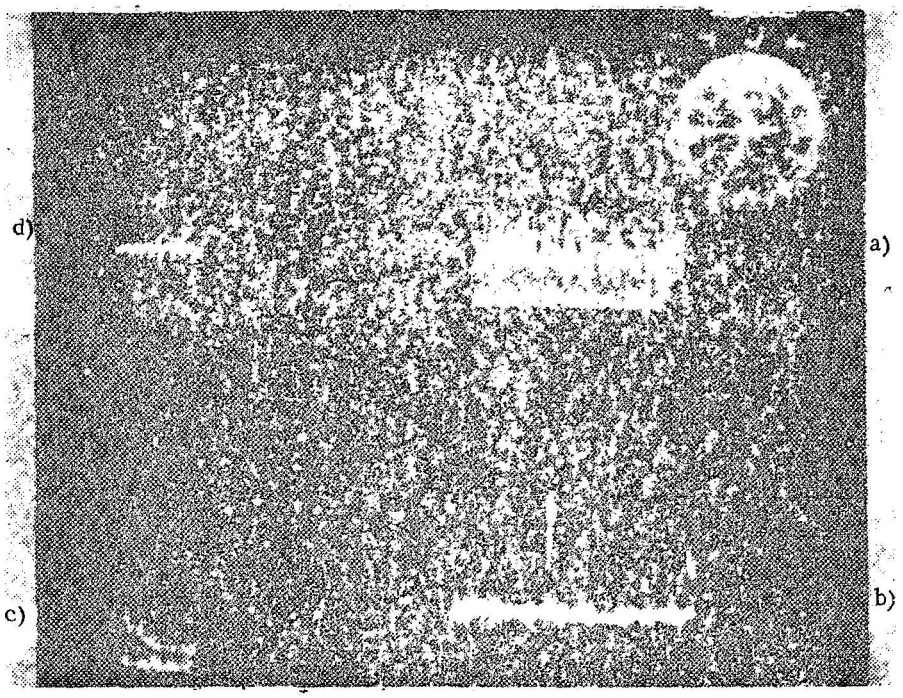

Figure 2. Frame: (a) Amplitude-Time Curve for Two Antennas (Scanning Time 0.1 sec); (b) Range Resolution (Range Calculated on the Basis of a Single Pulse); (c) Amplitude-Time Curve (Scanning Time 1 sec); (d) Time Marks for Slow Scan.

With random orientation of the meteor tracks, even with orthogonality of the $\vec{E}_1$ and $\vec{E}_2$ vectors, the portion of energy emitted by one antenna, after scattering by the meteor track, may be picked up by the second antenna. This will take place in those instances when the scattering coefficient is dependent on the form of polarization. It is also necessary to consider in this regard the spatial differential of the antennas (the distance between the antennas is 10 m) which causes a shift in the phase of the received signals by the angle φ_0.

In examining the geometric pattern of scattering under these conditions, we can show that for a modulus of the electric component of the received signals the following relationships are valid

$$E_1^2 \infty g_{11}^2\{\cos^4\theta + \sin\theta\cos\theta(1+\rho^2) + 2\rho\cdot\sin^3\theta\cdot\cos\theta\times \times[\rho\cos\varphi_0 - \cos(\psi+\varphi_0)] + 2\cos^3\theta\cdot\sin\theta[\rho\cdot\cos(\varphi_0-\psi) - \cos\varphi_0] + \rho^2\sin^4\theta\}; \quad (1)$$

$$E_2^2 \infty g_{11}^2\{\sin^4\theta + \sin\theta\cdot\cos^2\theta(1+\rho^2) + 2\rho\cos^3\theta\cdot\sin\theta\times \times[\rho\cdot\cos\varphi_0 - \cos(\psi+\varphi_0)] + 2\cos\theta\cdot\sin^3\theta[\rho\cdot\cos(\varphi_0-\psi) - \cos\varphi_0] + \rho^2\cos^4\theta\}, \quad (2)$$

where g_{11} is the scattering coefficient with parallel polarization, ρ is the theoretical value of the polarization ratio, θ is the angle between the vector $\vec{E}_1$ and the axis of the track, and φ is the phase shift due to the spacing of the antennas. /33

An analysis of the envelopes plotted in accordance with (1) and (2) will show that the polarization effect occurs in a wide range of angles θ, disappearing a comparatively narrow region near $\theta = 45°$. The polarization ratio ρ_{max} at angles of $\pm 30°$ relative to the axis of the antenna (i.e., within the limits of the major lobe of the directionality diagram) is less than its value at $\theta = 0°$ and $\varphi_0 = 0°$ on the average at 10%. The nature of the amplitude-time relationship is also somewhat variable. The general nature of the envelope with polarization which is nearly perpendicular is retained. The envelope for polarization which is nearly parallel is markedly changed at the origin (Figure 3). The nature of the relationship $\rho(t)$ is basically retained.

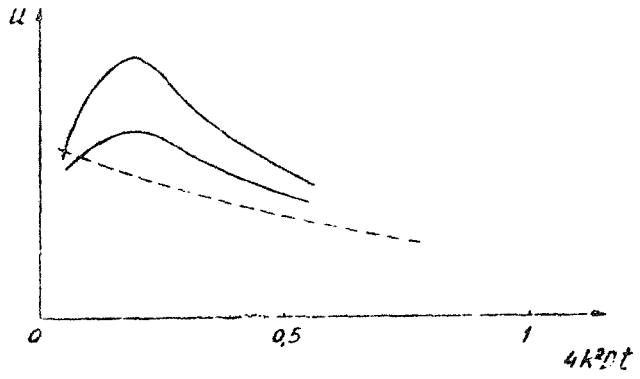

Figure 3. Example of Calculated Envelope ($\theta = 20°$, $\varphi^0 = 45°$). The dashed curve shows the envelope for parallel polarization in the ideal case.

3. Results of the Observations

The total time of observation during March 1962 was 50 hours. During this time, approximately 1,300 meteors were recorded on film. Hence, the average hourly number was 26. It is important to note that scanning took place only when the level of signals picked up by both antennas exceeded the threshold value, amounting to approximately 5 noise levels. From the total number of reflections obtained, we discarded the reflections that were limited at the top and also had a very small duration (several scanning periods). The others were used for analysis. Figures 4 and 5 show the distribution for these meteors in regard to range and velocities.

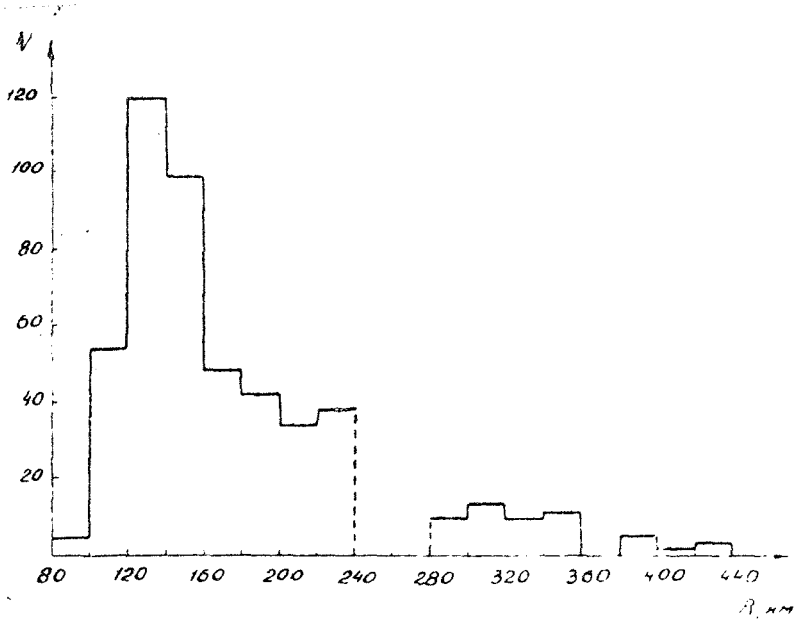

Figure 4. Distribution of All Meteors Used for Analysis as a Function of Range.

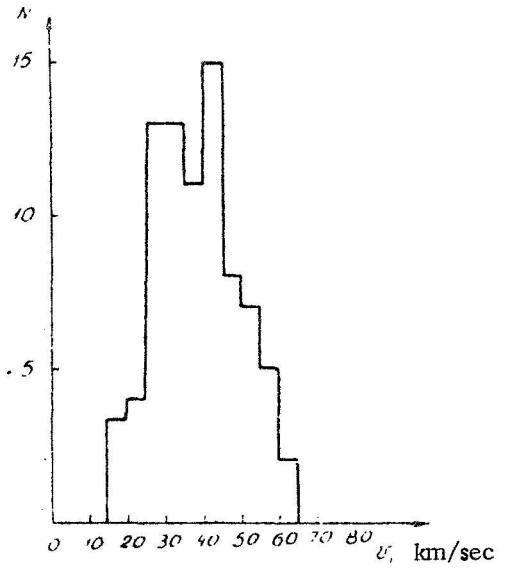

Figure 5. Distribution of Meteor Velocities During the Observation Period.

All of the reflections obtained were divided into two types: 1) reflections which did not show a polarization effect and 2) reflections which did show this effect.

In the first case, the envelopes of the signals which were picked up by two antennas either coincided absolutely or were similar during the entire duration of the echoes. The second type consisted of those reflections for which the amplitude-time relationships of the signals picked up by the two antennas. Reflections of this type amounted to 65% of the total number of echoes used for analysis. Characteristic echoes of the second type are shown in Figure 6. /34

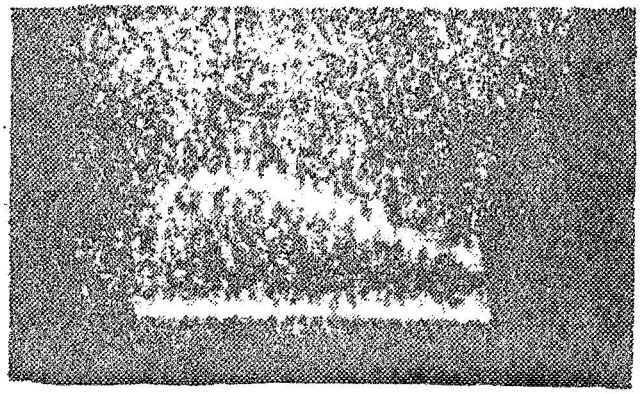

Figure 6. Characteristic Echo in the Presence of a Polarization Effect (Echo Duration 1 second).

For reflections that showed a polarization effect we found the distribution of the maximum polarization ratio ρ_{max} (Figure 7) which was determined according to the formula

$$\rho max = \frac{\rho max\, meas.}{\rho_\infty},$$

where $\rho_{max_{meas.}}$ is the maximum value of the ratio of the two signals and ρ_∞ is the ratio of two signals after the end of resonance. /35

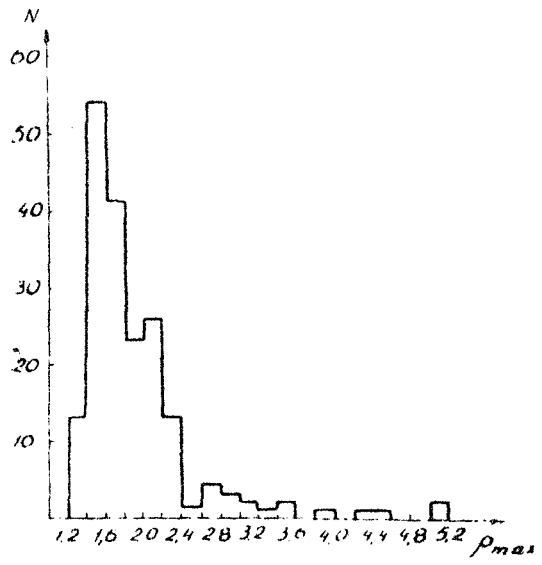

Figure 7. Maximum Value of Polarization Ratio for All Echoes Showing the Polarization Effect.

The maximum value of ρ_{max} = = 5.2, the distribution mode ρ_{max} = 1.4-1.6, and the average value of $\rho_{max\ av}$ = 1.85. The calculated value ρ_{max} for resonant tracks with $\alpha = 2.5\ 10^{11}$ electrons per cm was ~1.75. Hence, a considerable portion of the reflections have ρ_{max} somewhat greater than the calculated value. A similar result was obtained when measuring ρ_{max} for shower meteors [6]. The authors of this paper explain the recording of high ρ_{max} by the influence of the shift in the diffraction patterns due to resonance. In our observations, the duration of resonance was significant and the resonance peak in the overwhelming majority of cases was observed when /36 the formation of the diffraction pattern was already complete. Hence, the recording of high ρ_{max} must be considered as a deviation from the theory.

It is very interesting to study the distribution of the resonant meteors as a function of altitude. The apparatus used for this purpose did not make it possible to carry out direct measurements of the heights of the reflecting points. Therefore, the altitude was determined approximately by measuring the diffusion coefficient as a function of the decay time of the envelopes [12]. The distributions obtained (separately for the resonant and nonresonant echoes) agree with the theoretical concepts which state that meteor tracks which show the polarization effect must be located in the lower part of the meteor zone (Figure 8). For meteors which show the polarization effect, the distribution mode (87 + 89) km, h_{av} = 88.5 km, h_{max} = 94 km. For meteors of the first type, the corresponding values are (93 - 95) km, 92.5 km and 98 km.

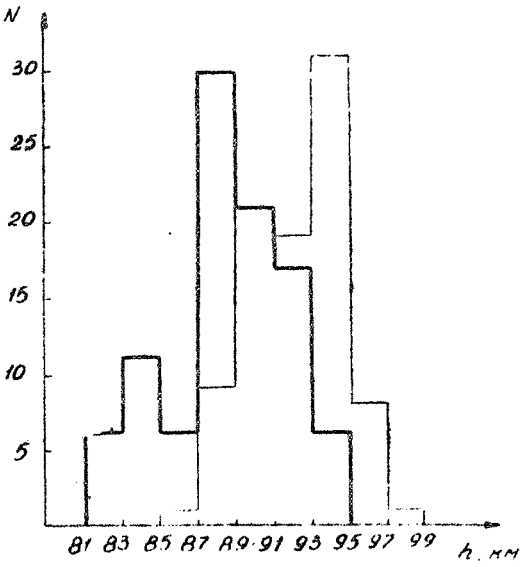

Figure 8. Distribution of Meteor Altitudes: —, nonresonant echoes; ▬▬, resonant echoes.

The distribution of the elevations of the reflecting point β (Figure 9) were plotted separately for the meteors of the first and second types. The elevation was determined on the basis of the formula

$$\beta = \arcsin \frac{h}{R}.$$

As we can see from the figure, the elevations for the resonant meteors lie primarily in the vicinity of β = 45°. At this angle, however, we also find the maximum of the major lobe of the directionality diagram of the antenna. Such a distribution may be caused by the concentration of reflection points of resonant meteors near the maximum of the major lobe, where the vectors E_1 and E_2 of the two antennas are approximately orthogonal. No such concentration was observed for nonresonant meteors.

For reflections with a pronounced resonance maximum, we determined the approximate electron density α by measuring the time of appearance of the resonance peak t_{res}. /37

It follows from the theory of Kaiser and Closs [1]

$$\alpha \cong 2.9 \cdot D t_{res} \cdot 10^{-12} \frac{\text{electrons}}{\text{см}}.$$

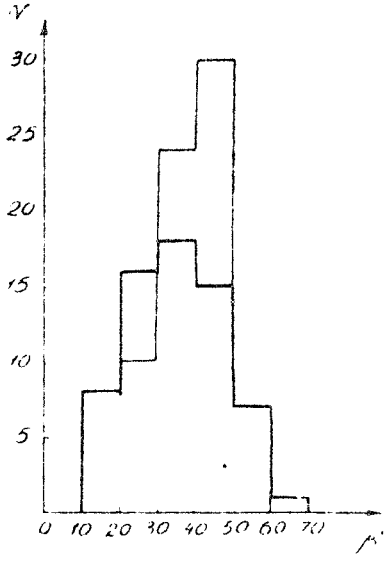

Figure 9. Distribution of Elevations of Reflecting Points: ——, resonant echoes; ▬▬, nonresonant echoes.

The distribution which we obtained (10) is in good agreement with the theory which states that α must be less than $2.4 \cdot 10^{12}$ electrons/cm. The distribution of the resonance duration which was obtained τ_{res} is shown in Figure 11, and the dependence of τ_{res} upon altitude is shown in Figure 12. The calculated value for the resonance duration for $\alpha = 3 \cdot 10^{11}$ electrons/cm and $D = 2.5$ m^2/sec is $\tau_{res} \simeq 0.2$ sec, which is in good agreement with the experimental data. According to the observations, we most often find

$$\alpha = (2 : 4)10^{11} \cdot \frac{\text{electrons}}{\text{cm}}, \quad D = (1.5 : 2.5) \frac{\text{M}^2}{\text{sec}} \text{ and } \tau_{res} = (0.1 : 0.2) \text{ sec.}$$

One of the problems of the experimental determination of the resonance effect is the confirmation of the existence of distortions of the diffraction patterns, predicted by calculation. Observation of these deviations in the diffraction patterns was complicated by several factors.

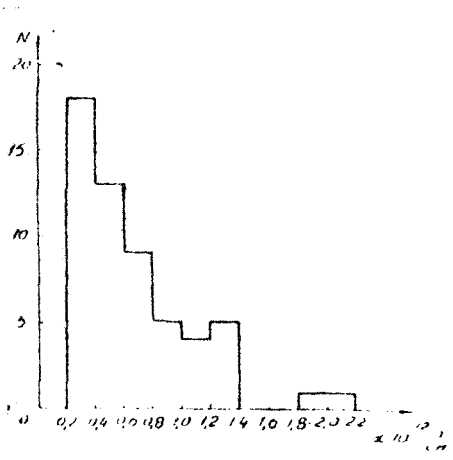

Figure 10. Distribution of Measured Resonance Durations.

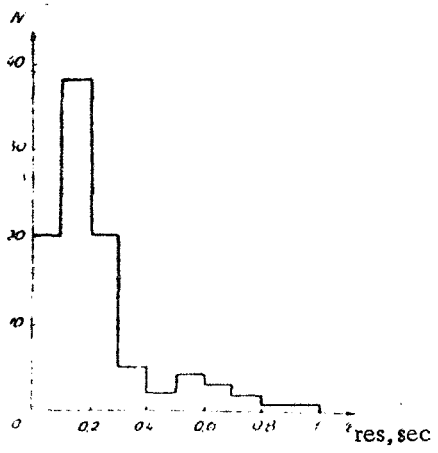

Figure 11. Dependence of Resonance Duration on Altitude: ▬, theoretical relationship for $\alpha = 5 \cdot 10^{11}$ electrons/cm, calculated according to the formula $\tau_{res} \sim 3\alpha\lambda^2/16\pi^2 D \cdot 10^{12}$ sec.

In the first place, the non-orthogonality of the vectors $\vec{E}_1$ and $\vec{E}_2$, with a random angle of polarization θ, smoothed over the regular effects and introduced additional random variations.

Secondly, the sensitivity of the apparatus used made it possible to observe low-density meteor tracks primarily with the relationship $U_c/U_M < 10$, since clear diffraction patterns were observed in a comparatively small number of meteors. Regardless of this fact, we succeeded in obtaining a significant number of envelopes for which the deviations predicted by theory were characteristic [10].

Out of 34 reflections with a diffraction pattern which was pronounced for both envelopes, 18 showed the absence of a lag or a very small lag (~10% of T_1), for 14--$\Delta t_1/T_1$ (0.2 to 0.4), for 2--more than 0.4 (Figure 13). /38

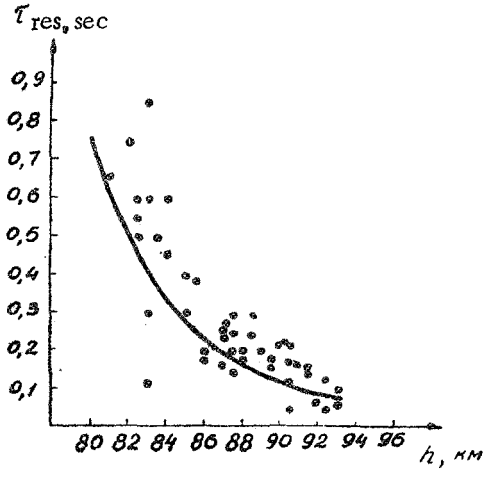

Figure 12. Distribution of Linear Electron Density for Resonant Tracks.

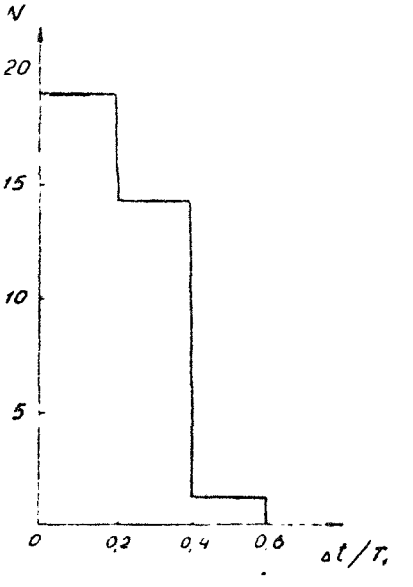

Figure 13. Distribution of Delay Times of Diffraction Patterns. Δt = delay time; T_1, first period of pulsations.

Reflections showed a marked reduction of the height of the pulsations all the way to a complete smoothing of the diffraction pattern with perpendicular polarization (Figure 14 a). While as in the case of parallel polarization the pulsations of the envelope were very clearly pronounced. The observed change in the periods of the pulsations corresponded to the calculated values both in appearance and in quantitative respect (Figure 14 b). Figure 15 shows the calculated envelopes.

However, the statistical characteristics of these effects were not obtained due to incompleteness of the apparatus.

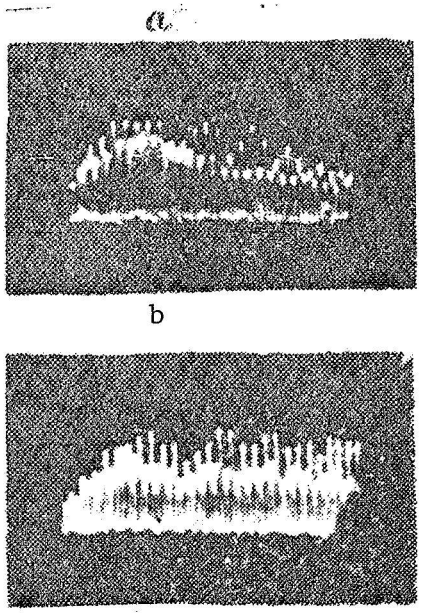

Figure 14. a) Echo Showing Smoothing of the Pulsations with Perpendicular Polarization; b) Diffraction Pattern for Two Forms of Polarization: large amplitudes for perpendicular polarization, small amplitudes for parallel polarization.

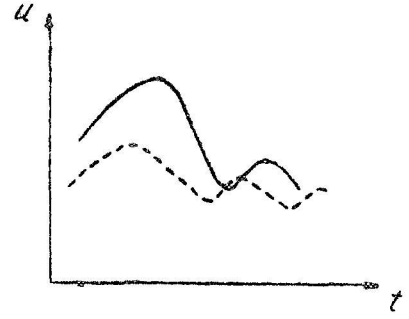

Figure 15. Calculated Envelopes for $\alpha = 3 \cdot 10^{11}$ electrons/cm, $l_{res} / \sqrt{R^{\lambda}} = 1.3$, $r_n = 40$ cm [13].

An interesting feature of the results obtained was the presence of a significant number of reflections whose nature could not be explained by theory [1]. These were the echoes of long duration with envelopes characteristic for intermediate and condensed tracks, showing the polarization effect (Figure 15). The dependence of the amplitude-time pattern on the nature of the polarization was observed in approximately 10% of the tracks of this kind. /39

Apparently, in order to explain these results we will have to discuss several of the possible mechanisms of resonance which differ from those taken up in [1].

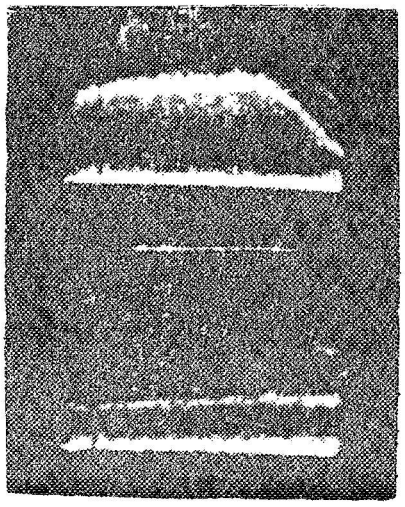

Figure 16. Examples of Reflections Showing the Polarization Effect in the Case of Intermediate and Condensed Tracks.

Conclusions

1. In observing sporadic meteors, when ionized tracks are oriented in a random fashion relative to the plane of polarization of the incident wave, approximately 65% of all the reflections show a polarization effect. The polarization effect is observed in approximately 10% of the cases for condensed tracks.

2. The resonance effect is characteristic especially of tracks that are located in the lower part of the meteor zone.

3. The values ρ_{max} in the majority of cases are close to the theoretical values. In some parts of the tracks, ρ_{max} is much greater than the calculated values.

4. The duration of resonance λ = 10 m amounts to a tenth of a second, decreasing with altitude. The experimental values show good agreement with calcualted ones.

5. The observations confirm the deviation of the diffraction pattern caused by the resonance effect predicted by calculations.

6. It is necessary to perform further studies in order to clarify the polarization effect as it concerns condensed tracks, as well as to obtain reliable statistical characteristics for the deviation of diffraction patterns.

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